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TUNNEL GRADIENTS AND AURAL HEALTH CRITERIA FOR TRAIN PASSENGERS

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ABSTRACT

An inconvenient consequence of the UIC health and safety criterion for allowable pressure changes in railway tunnels is highlighted. It is shown that the criterion limits allowable speeds in long tunnels with large changes of elevation much more than it does in equivalent tunnels with small changes in elevation. The constraint is especially strong for trains travelling uphill, but it can also exist for trains travelling downhill. Possible ways of avoiding the problem without reducing speed are considered and are found to be practicable in some cases. However, they are of uncertain suitability because they rely on exploiting a particular feature of the safety criterion in a manner that is unlikely to have been intended when it was mandated. In addition, attention is drawn to an ambiguity inherent in the application of the criterion to certain types of tunnel. Suggestions are made for simple modifications to the criterion and comparisons are made with conditions experienced routinely in commercial aviation.

1 INTRODUCTION

The consequences of airflows caused by trains in tunnels have been considered since the early days of railways [1-4]. In the eighteenth and early nineteenth centuries, attention focussed on topics such as ventilation, smoke movement and aerodynamic drag, all of which can be assessed quite well by steady-flow approximations. The existence of highly unsteady phenomena such as pressure waves was recognised almost a century ago [5] and papers addressing the alleviation of their consequences began to appear at least 50 years ago [6,7]. Soon afterwards, considerable attention began to be paid to reducing the risk of sonic booms radiating from tunnel exit portals during wave reflections [8,9] and future concerns include similar effects propagating from entrance portals during train-entry to a tunnel [10]. Today, it is standard practice to address such issues in the design of new tunnels and good quality theoretical tools are readily available for both one-dimensional and three-dimensional analyses. Nevertheless, taxing issues can still arise in design, especially as a consequence of a continuing trend towards ever higher speeds coupled with a desire for small tunnel cross-sections to reduce capital costs.

Pressure disturbances are generated whenever the front (nose) or rear (tail) of a train cross a discontinuity in a tunnel. The most obvious discontinuities are the tunnel entrance and exit portals, but account must also be taken of features such as shafts and cross-passages and, indeed, of events when two trains cross. The magnitudes of the resulting waves depend strongly on the train speed V_z and the area blockage ratio β (i.e. the ratio of the cross-sectional areas of the train and the tunnel). Other factors such as the lengths and resistance characteristics of the trains and tunnels are also important, but these are usually less critical. Typically, the amplitudes of the key pressure disturbances vary approximately with V_z^2 and with β^n, where n exceeds 1.5. Thus, it is obvious why aspirations for increased speed conflict with those for reduced construction costs.

Pressure disturbances in tunnels are important for several reasons, ranging from structural forces on trains and tunnel infrastructure [11] to the possibility of emitting sonic booms into the environment outside the tunnel [12,13]. In this paper, however, attention is focussed on a consequence that has been well known for many decades, namely aural sensations experienced by passengers on trains. There are two issues to consider, namely (i) comfort and (ii) health and safety and, in nearly all cases, the former are more constraining than the latter. Broadly speaking, comfort criteria determine the acceptability of conditions expected during routine operation whereas safety criteria determine the acceptability of rare, non-routine events such as sudden pressurisation or de-pressurisation following window breakage.

A UIC leaflet [14] gives criteria for both comfort and safety. The comfort criteria are designed to ensure that a large majority of passengers will experience no significant discomfort. They have the status of guidelines, not mandatory requirements, because railway operators reasonably opt to choose different criteria for different sections of railway (e.g. long *vs* short tunnels, single-track *vs* twin-track, high-speed *vs* low speed, sealed *vs* unsealed trains). In contrast, the health and safety criterion is mandatory, being governed by medical factors rather than more tenuous factors associated with perceptions of "comfort". It is designed to minimise the risk that any passenger will suffer harm, even if they have aural defects – as a result of surgery, perhaps, or as a result of a cold (e.g. blocked Eustachian tubes). The prescribed limiting pressure changes are far below values that would pose a safety risk to normal, healthy persons.

Although the comfort criteria are nearly always more demanding than the safety criterion, it is possible for the opposite to be true. This paper focusses on one such case, namely long railway tunnels with relatively steep gradients. For this rare case, the internationally accepted safety criterion can be severely limiting and, indeed, it completely rules out some notionally possible tunnels. At first sight, this should simply be accepted as an inevitable consequence of the need to respect health and safety.

That is, such tunnels should be redesigned so that they satisfy the criterion. However, it is shown below that simple changes to a non-compliant tunnel configuration can sometimes enable the criterion to be satisfied without necessarily improving the medical prognosis. This can create potential dilemmas for railway owners wishing to build such tunnels. It also demonstrates that the safety criterion in its present form is not universally satisfactory. It is simple, it is widely effective, and it has served its purpose very well indeed for many years, but it is beginning to have consequences that are unlikely to have been intended when it was mandated. Accordingly, it is sensible to re-visit the basis of the criterion to ascertain whether it could reasonably be relaxed in particular circumstances.

1.1 Outline of paper

The next sections of the paper present typical pressure histories in tunnels and show how the comfort and safety criteria relate to these. Then the particular case of long tunnels with steep gradients is considered and the anomalous behaviour is illustrated. This is followed by a brief analysis of representative construction costs of tunnel modifications that would nominally circumvent the problem and, after a discussion of implications for high speed rail in general, the paper concludes with a summary and recommendations.

2 PRESSURE HISTORIES IN LONG AND SHORT TUNNELS

Figures 1 & 2 show predicted pressure histories on high-speed trains in two Spanish tunnels, one short and one long. Brief details of the tunnels (Tendero and Guadarrama) are given in Table-1 and, although not important for the present paper, further details can be found elsewhere [15]. Train data are given in Table-2. To simplify comparisons later in the paper, both tunnels are treated as if they were horizontal even though the true tunnels have elevation gradients. In the shorter tunnel, there are two trains, one in each direction, with one entering the tunnel 4 seconds after the other. In the longer tunnel, which is of smaller cross-section, only one train is simulated. In each case, the assumed train speed is constant and equal to 300 km/h.

Table-1 Tendero and Guadarrama Tunnel data

Tunnel	Type	Length (m)	Cross-sectional area (m^2)	Slope (%)
Tendero	Double Track	1,097	103	2.16 & -1.56
Guadarrama	Single Track	28,400	52	0.44

Table-2 Train data

Tunnel	Train	Length (m)	Cross-sectional area (m^2)		Friction coefficient ($f = \lambda/4$)
			Power cars	Coaches	
Tendero	Train-1	208	11.84	9.90	0.003
	Train-2	273	11.84	9.90	0.003
Guadarrama	Single Track	400	11.84	9.90	0.003

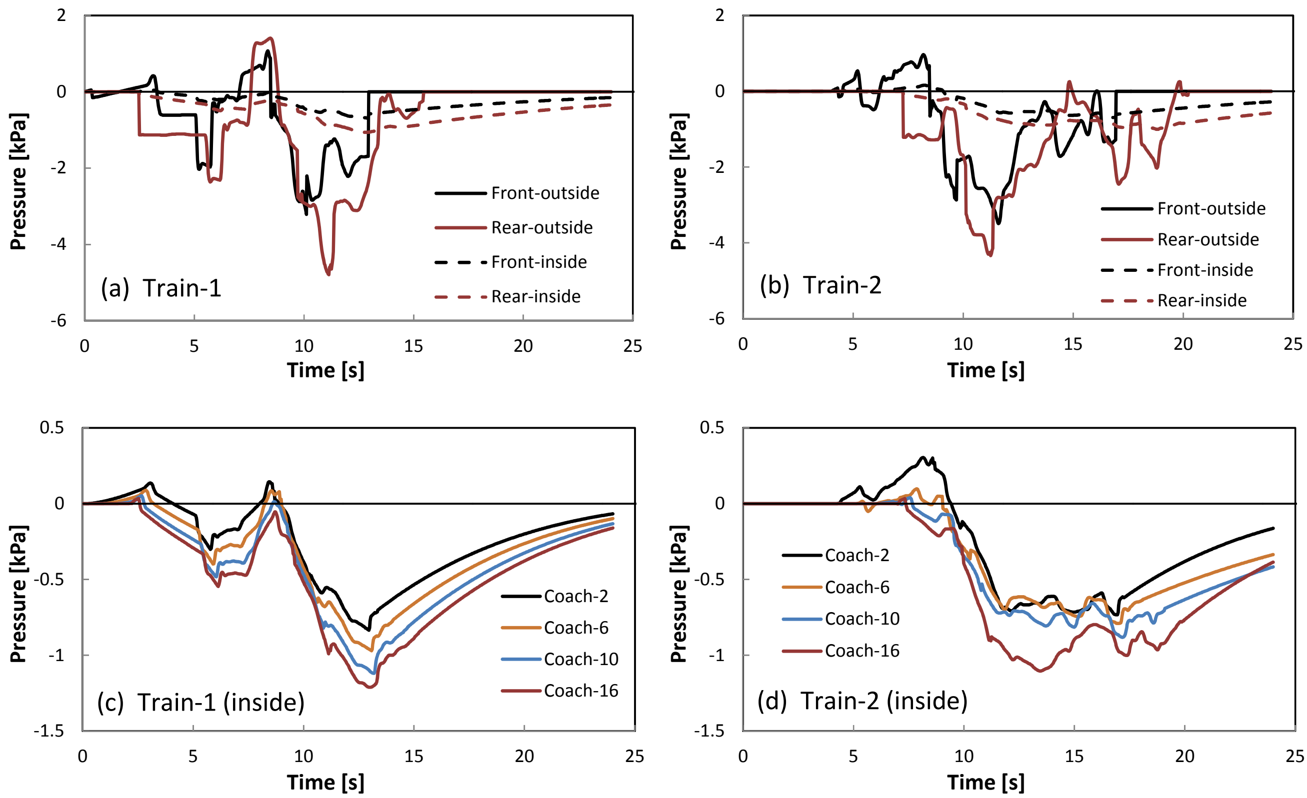

Fig-1 Tendero Tunnel (horizontal), sealed trains at 300 km/h

(a),(b) Pressures outside and inside the front and rear of crossing trains

(c),(d) Pressures inside coaches along the trains

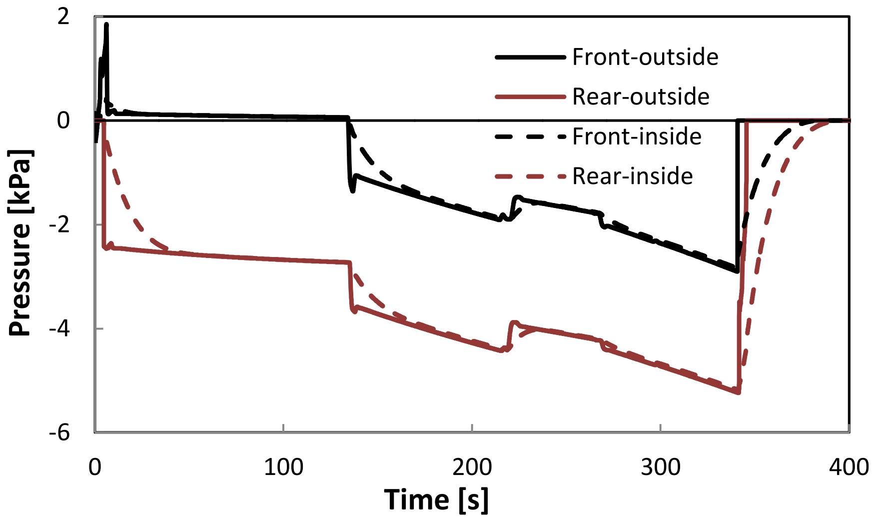

Fig-2 Guadarrama Tunnel (horizontal), sealed train at 300 km/h:
Pressures outside and inside the front and rear of the train

Most of the sudden pressure changes in the Figures correspond to periods when the principal wavefronts and their subsequent reflections pass alongside the trains. In both cases, the principal wavefronts are generated during nose-entry, tail-entry, nose-exit and tail-exit, although passengers on the trains never experience the last of these from their own train. Furthermore, they do not experience the first of them (i.e. nose-entry) until after it has reflected from the remote end of the tunnel and/or from other locations along the tunnel. The amplitudes of the wavefronts are broadly similar in the two cases, but the time intervals between successive events are far greater in the longer tunnel because of the increased time required for wavefronts to propagate along it. For the crossing-trains journey, there are two sets of pressure waves and there is also a strong, short-lived, reduction in pressure during the period when the trains cross. Accordingly, the pressure histories are more complex than in a single-train case. Furthermore, the particular outcome is strongly dependent upon the relative times of entry of the two trains - because the histories are a combination of (i) the superposition of two sets of waves and (ii) a train-crossing event (between about 8.5 s and 11.4 s).

The continuous lines in Figs-1 & 2 show pressure histories that would be experienced by passengers if the trains were unsealed and the broken line shows corresponding histories assuming that the trains are sealed. The graphs shown are applicable for a dynamic sealing time constant of 10 s, but the particular value is not important for the purposes of this paper. Instead, it is the characteristic difference between outcomes with sealed and unsealed trains that is important. By inspection, the sealing greatly extends the time needed for a sudden change to influence internal pressures, but it has relatively little influence on long-term changes. These qualitative differences in behaviour are allowed for in the UIC Guidelines by recommending different comfort criteria for sealed and unsealed trains.

The big differences between outcomes with sealed and unsealed trains constitute an important driver for railways, partly because of the inherent improvements in comfort, but also because the sealing has the effect of reducing the minimum acceptable cross-sectional area of a tunnel. That is, a valuable trade-off is enabled between increased vehicle costs and reduced construction costs. In principle, it would be conceivable to follow this path to extremes by making trains almost totally leak-proof and thereby enabling tunnels cross-sections to be very small indeed. However, the safety criterion limits the scope for this approach because it requires designers to allow for rare, but foreseeable events such as the sudden failure of a window. If this were to happen, passengers would almost instantly experience the unsealed conditions instead of the sealed conditions that would normally prevail.

3 PRESSURE CRITERIA

3.1 Health and safety criteria

The human ear is a complex organ that performs many functions and has some remarkably delicate components. The consequences of damage to ears can range from short-term inconvenience to long-term disability with strong implications for a person's lifestyle. It is proper that this matter is taken very seriously indeed in the development of standards for railway design and operation. When the need for internationally accepted criteria was recognised several decades ago, the European railway community set up an investigating committee charged with the task of proposing criteria founded on sound, well-reasoned principles. The committee took extensive advice (medical, legal and sociological as well as technical), reviewed detailed work from member railways and commissioned a number of dedicated studies before issuing its proposals. It is a tribute to the work of that group that its proposals [16] were widely accepted at the time and, in large measure, are still accepted today despite considerable subsequent advances in technology. Notwithstanding the complex nature of the issues, the chosen criterion is remarkably straightforward and free from ambiguity. It is a simple requirement that the maximum pressure change experienced during a journey through a tunnel must not exceed 10 kPa. As indicated above, this requirement must be satisfied even in the event of reasonably foreseeable, but extremely rare, incidents. It allows for the possibility that persons with severe aural defects might be at risk of further damage if changes significantly larger than 10 kPa were to occur. It also allows for the fact that some persons with aural defects can need a very large time to adjust to a change in pressure, even if it occurs gradually.

3.2 Comfort criteria

In contrast with the safety criterion, *comfort* criteria presented in UIC documentation [14] are not mandatory. Instead, they are *guidelines* giving recommended upper limits. This distinction is important because railways need to have the flexibility to choose comfort standards based on their commercial needs. Nevertheless, the comfort criteria are likely to be a good starting point for the design of new railways. The criteria are applicable to conditions in routine operation and their development has involved structured test programmes with volunteers in laboratory-based pressure chambers and in-service surveys of passenger responses to pressures during routine journeys [17-20]. In practice, the discomfort expressed in relation to greater pressure changes depends upon the time available to adjust to them before further significant changes occur. Also, it is found that very few people report discomfort to pressure changes smaller than about 0.5 kPa however rapidly these occur (within timescales that are possible in tunnels operation).

For services using *unsealed* trains, it is common to choose a single comfort criterion. Upper limits recommended in Appendix F.4 of the UIC leaflet [14] are:

- For single-track tunnels: "not more than 3.0 kPa in 4 secs"
- For twin-track tunnels: "not more than 4.5 kPa in 4 secs"

At first sight, the second of these criteria appears to be more lax than the first, but this is not necessarily the case. The twin-track limit includes an implicit allowance for sudden pressure changes during train crossing so single-train journeys at the same speed in the same tunnel will always yield much smaller changes than the 4.5 kPa limit. In effect, the two criteria may be interpreted as an implicit acknowledgement that high-probability events should satisfy more demanding criteria than low-probability events. Indeed, an approach formerly used by DB [21] recognised this explicitly by using a single criterion in all types of tunnel (2.5 kPa in 3 secs), but stipulating that this did not need to be satisfied during train-crossing events. In practice, it would be rare for the above UIC criteria to exclude events that satisfied this simple criterion, but there is nevertheless advantage in prescribing explicit limits for all possible conditions.

In practice, the unsealed-train criteria are applied to conditions such as those shown by the continuous lines in Figs-1&2. In contrast, *sealed*-train criteria are applied to the very different conditions characterised by the broken lines in the figures. Instead of stipulating a single criterion, it is normal to stipulate several independent criteria, all of which are required to be satisfied. Thus, for example, the recommended limits in Appendix F.4 of the UIC leaflet [14] are:

- not more than 1.0 kPa in 1 sec
- not more than 1.6 kPa in 4 sec
- not more than 2.0 kPa in 10 sec

Identical values are used for single-train journeys and for crossing-train journeys. The small-time criteria relate primarily to aural response to sudden, discrete changes whereas the large-time criteria relate to the ability of the ear to adjust to the cumulative effect of multiple small changes.

By inspection, the sealed-train criteria tend to be much more demanding than the unsealed-train criteria. At first sight, this can be surprising because both are applied to all passengers. However, sealed trains are much more costly than unsealed trains and so are used only in railways where extra-high standards are applied to the whole travel experience and can be reflected in the fare structures.

3.3 Aircraft pressure criteria

It is instructive to compare the above criteria with pressures experienced routinely in commercial aviation. The total change in pressure inside the passenger cabin of an aircraft between ground level and cruising flight level is typically around 20 kPa and typical rates of change of pressure during ascent and descent are about 0.03 kPa/s and 0.02 kPa/s respectively [22]. Expressed in the same manner as the railway comfort criteria, the changes during ascent and descent correspond approximately to "20 kPa in 650 s" and "20 kPa in 1000 s" respectively. Thus the average rates of change are much smaller than those allowed for short periods inside trains, but the overall change is much greater than inside a train.

Although the pressure *inside* the passenger cabin at cruising altitude is maintained at about 0.8 bar, the pressure *outside* the aircraft can be much smaller – less than 0.3 bar. As a consequence, the pressure difference between inside and outside can be at least 0.5 bar. Therefore, in the exceptional case of a sudden loss of pressurisation for any reason, passengers could be exposed to a sudden pressure change of more than 50 kPa, which is very much greater than the railway safety criterion of 10 kPa.

At this stage in the paper, the purpose of these comparisons is simply to explain that permitted overall pressure changes on board aeroplanes greatly exceed those on board trains whereas the rates of change of pressure on board aeroplanes are much smaller than those experienced on board trains. For completeness, however, it is also noted that there are many differences between air travel and rail travel and typical pressure histories experienced by passengers in the two cases are very different. Therefore, it would be unwise to jump to conclusions about the validity of the criteria for one mode of travel based on an assessment of criteria for the other mode. Furthermore, most members of the public are aware of potential ear discomfort during air travel, but few consider this to be possibility during rail travel. Even passengers with aural defects might have received little or no guidance in this respect.

4 SENSITIVITY TO ELEVATION CHANGE IN LONG TUNNELS

The safety criterion is considered primarily as a back-stop device designed to ensure that possible, but highly unlikely events such as sudden depressurisation will be most unlikely to cause harm to passengers even if they have aural defects. However, in at least one special case, it can have a strong influence on conditions than could occur routinely during *normal* operation. This is when a relatively small (and, perhaps, seemingly benign) rate of change of pressure persists for an unusually long time, in a manner somewhat similar to that on board an aircraft. In such cases, differences in the qualitative forms of the comfort and safety criteria assume a critical importance.

Each of the comfort criteria listed above has the same general form, namely the stipulation of a maximum permissible pressure change Δp_c in a prescribed time interval Δt_c. In principle, it is permissible for each successive interval Δt_c to have an *additional* pressure change of up to Δp_c. Accordingly, it would be permissible to have a sustained, steady pressure increase (or decrease) of any duration with a gradient of $\Delta p_c / \Delta t_c$. Eventually, however, this continuing rate of change would violate the safety criterion, because this limits the maximum *total* change irrespective of the average rate at which it occurs.

One instance in which this behaviour occurs is a long tunnel with large differences in elevation – as is the case, for instance with the proposed Pajares Tunnel in Northern Spain, which has an elevation difference of about 420 m (see Appendix). The need for long tunnels with strong elevation changes is likely to be rare, but it is real nonetheless and it creates a dilemma for designers. Should they tell their client that the tunnel is not permitted under UIC rules or should they argue that an exception to the rules is justified, noting, for example, that an identical pressure history would be considered acceptable in routine aircraft operation?

4.1 Pressure change due to elevation change

In static conditions, atmospheric pressure typically reduces with height at a rate of about 12 Pa/m. Thus, for instance, a pressure difference of about 5 kPa will be normal between the portals of Pajares Tunnel simply because of its geographical location and this clearly limits the allowable scope for additional pressure fluctuations caused by trains without violating the existing safety criterion. Indeed, if another (hypothetical) tunnel had an elevation difference of around 850 m, the ambient pressure difference would be about 10 kPa and so *no* further changes would be possible. In the limit, therefore, one consequence of the criterion is to ban train operations in *any* tunnels with elevation changes as large as 850 m (although such operation would remain permissible over open ground). A more practical consequence is that it limits the scope for high-speed operation in tunnels with substantially smaller changes in elevation.

Figure 3 shows predicted pressure histories for two cases similar to Fig-2 except that the tunnel is 30 km long and it is imagined to have gradients of 1% and 2%. For simplicity, the gradients are assumed to be uniform along the whole tunnel. This is by no means the only possibility, but it is a useful idealisation because it avoids unnecessary complications when interpreting predicted pressure histories. In Fig-3(a), the train is travelling in the uphill direction so the elevation causes a continual background decrease in pressure that superimposes on train-induced pressure changes. In Fig-3(b), the train is travelling downhill and the background pressure change is a continual increase.

Notwithstanding the big differences in the predicted pressure histories, assessments by the *comfort* criteria lead to almost identical outcomes for the uphill and downhill cases because only events occurring in relatively short periods are relevant. In contrast, however, assessments by the *safety* criterion lead to strongly different conclusions. For the uphill case, the maximum predicted changes for gradients of 1% and 2% are 9.1 kPa and 12.3 kPa respectively and the second of these violates the safety criterion. The corresponding values for the downhill case are 9.0 kPa and 9.8 kPa respectively, both being below slightly below the criterion limit.

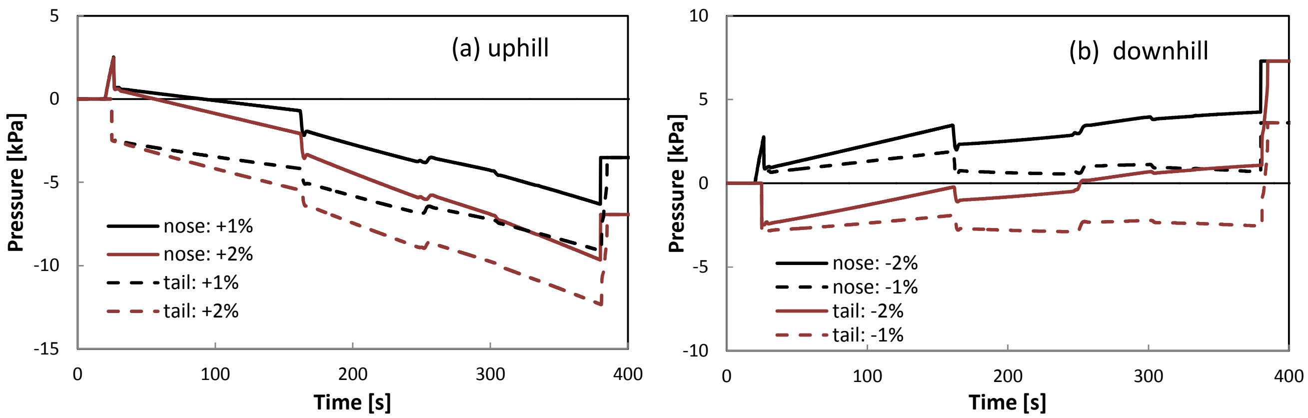

Fig-3 Influence of tunnel gradient on pressure alongside a train

Tunnel = 30km, 50m^2; Train = 400m, 12m^2, 300km/h

Although the need for tunnels such as this is rare, the example illustrates a fundamental difficulty facing railways considering the use of long tunnels for high-speed trains in mountainous territory. Such tunnels were not proposed several decades ago, but they are beginning to be proposed today. As a consequence, the safety criterion is beginning to have consequences that, irrespective of whether they were foreseen when it was originally mandated, have not previously pertained in practice. It is therefore reasonable to explore whether these consequences are truly justified by the benefits that the safety criterion provides.

In passing, it is worth mentioning that elevation differences are not the only possible cause of pressure differences between tunnel portals, especially in the case of long tunnels. Other possible causes include (i) differences between ambient atmospheric conditions - on opposite sides of a mountain range, for instance and (ii) atmospheric winds. Additional factors such as these should always be allowed for by designers, but they are not addressed explicitly herein.

4.2 Influence of tunnel gradient and train speed

Before considering possible changes to the safety criterion, it is useful to clarify the scope of the problem. Figure-4 shows predicted maximum pressure changes for a wide range of tunnel gradients and train speeds. The tunnel is 30 km long and its cross-sectional area is 50 m^2. The corresponding dimensions of the train, namely 400 m and 12 m^2, are typical of a wide range of high-speed trains, not specific to any particular train. No allowance is made for train sealing. The particular software used in the development of the figure (and all other simulations herein) is the one-dimensional program ThermoTun [23], but nearly identical results would be obtained with any other valid software package.

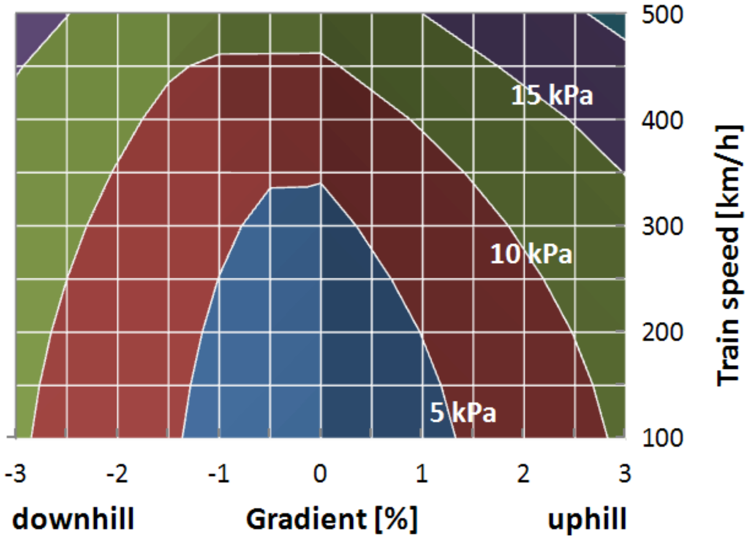

Fig-4 Influence of elevation on maximum pressure change, L_t = 30km, A_t = 50m^2

(*Contours denote 5, 10, 15 & 20 kPa*)

Consider first the case of a horizontal tunnel. For this case, the maximum train speed that will enable the safety criterion to be satisfied is about 462 km/h, which is higher than the service speed in any operational railway today. With average uphill gradients of 0.5%, 1.5% and 2.5%, however, the corresponding maximum allowable speeds are approximately 427 km/h, 340 km/h and 193 km/h respectively. With average *downhill* gradients of the same amplitudes, greater speeds are allowable, namely approximately 462 km/h, 434 km/h and 250 km/h respectively. When considering Fig-4, it should be noted that that the High Speed Infrastructure TSI does not permit average gradients exceeding 2.5%. Also, the design criteria are applicable to real tunnels so allowance should be made for approximations in software methodology and for uncertainties in the data used to define tunnel and train characteristics. In good design, therefore, rather smaller limiting speeds would be adopted – corresponding to maximum predicted changes of 9 kPa, say. Nevertheless, the above values will suffice for the purposes of this paper.

Similar figures could be developed easily for alternative train and tunnel geometries and resistance characteristics and, if desired, explicit allowance could be made for complicating factors such as non-equilibrium atmospheric conditions and the simultaneous presence of more than one train. Some such factors will exist in any practical design, but they will not change the qualitative trends shown in Fig-4 so negligible benefit would accrue from considering them explicitly herein.

The over-riding conclusion from the figure is that the requirement to satisfy the safety criterion will rarely be a limiting factor in design, even for train speeds of, say, 400 km/h. Nevertheless, the figure also demonstrates the decisive influence of the criterion in tunnels with large changes of elevation. Furthermore, unless the relentless drive for ever greater speeds and reduced construction costs ceases, the issue will become increasingly important in future. There will be pressure to identify cost-effective ways of achieving compliance with the safety criterion and, as shown below, there is a risk that this might sometimes result in designs that satisfy the letter of the law, but nevertheless violate its underlying purpose.

4.3 Influence of tunnel length

Strictly, Fig-4 is applicable only for the particular tunnel and train parameters shown in Tables-1 and 2. However, as a first approximation, the figure may be used for identical trains travelling in tunnels with much greater or smaller lengths (but similar cross-sectional and resistance properties). This interpretation of the figure is permissible only for tunnel lengths of several kilometres, but that is of little practical importance because large changes in elevation do not occur in short tunnels.

5 CONVENTIONAL REMEDIAL MEASURES

Attention now turns to considering possible methods of avoiding the undesirable consequences of large changes in elevation. As a preliminary, however, it is useful to consider common ways of reducing *dynamic* pressure changes in existing tunnels.

Increased tunnel cross-sectional area: Train-induced pressure fluctuations depend strongly on the train:tunnel blockage ratio so an obvious way to reduce them is to increase the tunnel cross-sectional area. As a rough guide, however, each 10 m^2 increase in area may cost in the order of €M 0.5 per kilometre so this is an unattractive option in long tunnels.

Multiple shafts along a tunnel: Dynamic pressure fluctuations can be reduced greatly by providing airshafts between the tunnel and the atmosphere. To be effective, however, the shafts need to be fairly closely spaced (usually less than 500 m) and their cross-sectional areas are typically of the order or 5% to 15% of the tunnel cross-sectional area. This is not a cost-effective approach in long tunnels.

Connections to an adjacent tunnel: As an alternative to shafts, connections are sometimes provided to an adjacent tunnel with the objective of reducing aerodynamic resistance (and hence the required train power). Such connections can also reduce the overall amplitudes of dynamic pressure fluctuations, but this potential is limited because each train causes fluctuations that are experienced by trains in the adjacent tunnel. Furthermore, the construction costs of multiple connections are high.

Increased train sealing: Compliance with *comfort* criteria can be increased by improving the sealing characteristics of trains. This is done routinely in most high speed railways around the world. In Japan, pressures inside trains are sometimes controlled actively by the use of high performance fans. This is an especially effective approach in the case of tunnels with significant changes in elevation if the control system is pre-programmed with data describing the rate of change of elevation [24]. Nevertheless, these approaches have little influence on compliance with the *safety* criterion because that must be satisfied even if the sealing (or pressure control system) fails.

Reduced train speed: Because the amplitudes of train-induced pressure waves are strongly dependent on the train speed, it is usually possible to reduce dynamic pressure changes significantly by means of a reduction in speed. This approach might be worth considering in short tunnels – taking advantage of modern signalling technology, perhaps – but it would be self-defeating in long tunnels designed specifically for high speed operation.

5.1 Relevance to tunnels with large changes in elevation

Although each of the above options is potentially suitable in some (perhaps many) short tunnels, all of them are undesirable for long tunnels, either on the grounds of feasibility or of high cost. Even more important for the purposes of the present paper, however, all of them influence only the dynamic component of pressure changes (i.e. pressure waves, etc). They have no influence whatsoever on the static (elevation-related) component of the changes. Thus, they are least effective in precisely those cases when the sought-after method needs to be most effective. Accordingly, a radically different approach is needed.

6 POSSIBLE WAYS FORWARD

In principle, there are at least three ways forward, namely:

- Decide that high speed operation is not acceptable in tunnels with large changes of elevation;
- Devise ways of working around the limitations created by the safety criterion;
- Revise the safety criterion.

The first of these approaches has obvious disadvantages for railway operators and passengers in mountainous regions. Therefore there is a strong incentive to explore the other two approaches carefully.

6.1 Working around the existing criterion

At least one potentially simple solution to the problem exists, exploiting the fact that the safety criterion applies independently to each tunnel, irrespective of the proximity of adjacent tunnels. To explore a possible consequence of this, consider the pressure histories shown in Fig-5a based on two 15 km long tunnels separated by a 100 m long overland section. The continuous lines show the pressure histories in the first of these tunnels and the broken lines show the corresponding histories in the second. The existence of the overland region causes the overall histories to be more complex than those in the simple 2% uphill case shown in Fig-3, but the maximum predicted pressure change in each tunnel (approximately 9 kPa) is below the safety limit. Accordingly, designers could, in principle, seek to satisfy the safety criterion by choosing a tunnel alignment that enables a short overland region to be created. This would be a professionally unsatisfying way around the problem, of course, but the illustration nevertheless demonstrates an inherent limitation of the criterion itself. To emphasize this point, Fig-5(b) shows a closely related case in which the long tunnel has a 250m long, large diameter shaft at its mid-length. By inspection, the predicted pressure histories closely resemble those presented in Fig-5(a) for the tunnel with an overland region. Indeed, the similarities are so strong that only tiny differences can be seen even when the two sets of predictions are superimposed on each other. Nevertheless, since there is only one tunnel, the pressure history in Fig-5(b) violates the safety criterion even though the almost identical pressure history in Fig-5(a) does not.

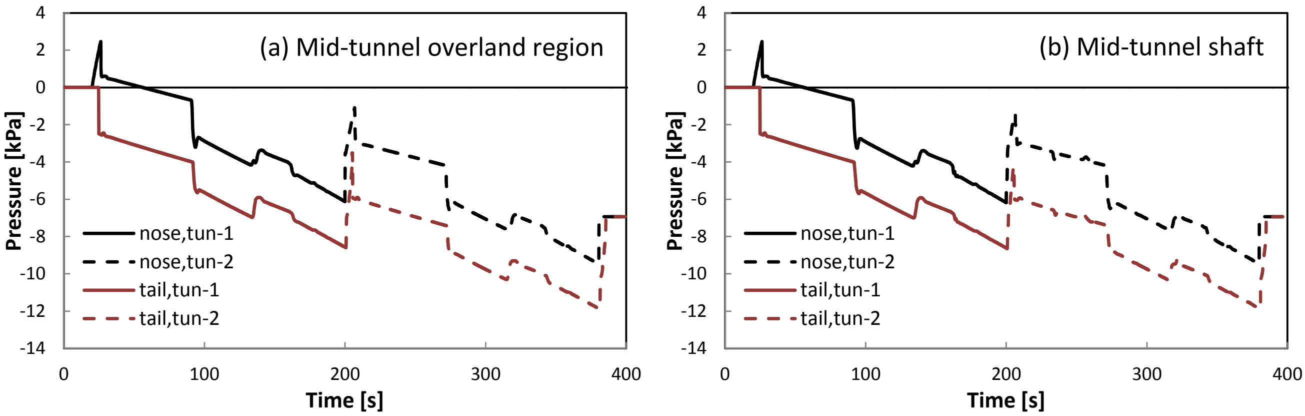

Fig-5 Separation of tunnel into two 15km sections
Tunnel = 30km, 50m^2; Train = 400m, 12m^2, 300km/h

6.2 Possible revised safety criterion

The UIC comfort and safety criteria have served the international railway community well. They should be changed only if there is a clear justification for doing so. The comfort criteria have the status of guidelines and they are used accordingly; many operators prescribe variations on the theme to suit local needs related to ride-quality and cost, etc. The safety criterion is widely accepted as mandatory, but, hitherto, it has rarely constrained practical design and so its greatest practical benefit has usually been the reassurance that it provides to designers and operators. This situation will continue to prevail in a large majority of future designs, but the fact that the criterion is a big constraining factor in special cases is justification for re-visiting the intentions that lay behind its development. It is possible, for instance, that the exceptionally simple form in which it is expressed was chosen in part because of the advantages of simplicity and clarity. Also, it is possible that greater attention was paid to tunnel operations of the sort that existed at the time than to hypothetical future operation in long tunnels with large elevation change.

Any revision to the criterion would clearly require review by the international railway and medical communities, but has potential to benefit the railways without adverse consequences for passengers. As a starting-point for such a review, a possible revised criterion can be suggested along the lines of the two-part criterion illustrated in Fig-6:

1. *The absolute change of pressure shall not exceed ΔP_A in any interval less than ΔT_A ;*
2. *The average rate of change of pressure shall not exceed $\Delta P_A / \Delta T_A$ in any interval greater ΔT_A .*

The existing criterion is shown as a horizontal line at a pressure of 10 kPa. Any pressure change below this line is deemed to be acceptable. The possible two-part criterion is illustrated for the particular case of ΔP_A = 10 kPa so that it is identical to the existing criterion for all intervals less than ΔT_A . However, it permits greater overall pressure changes in larger time intervals. The general form of this graph is already familiar in railway practice, albeit in a slightly different context. It is the form of the *comfort* criterion recommended in the Subway Environmental Design Handbook [25] and it is reported in UIC-779 itself [14]. The associated pressure changes and timescales for the comfort criterion are much smaller than those under consideration for the safety criterion, but the general concept is similar. It reflects a recognition that large pressure changes impose less threat to passengers when they occur over large time intervals than when they occur over small intervals. This is because of the ability of ears to adjust gradually to pressure change even if they cannot adjust rapidly (because of infection or defect, etc). Medical evidence demonstrating this characteristic was considered by the ERRI Committee that recommended the existing safety criterion [16].

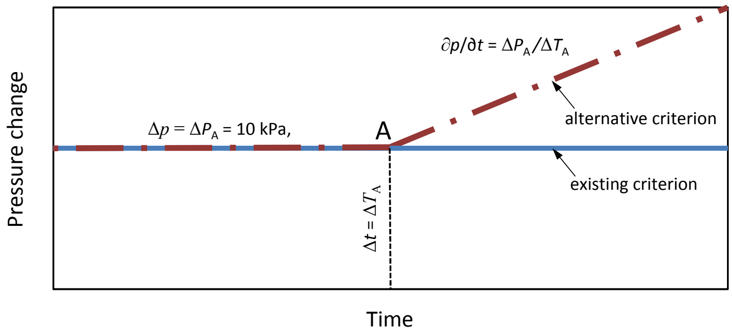

Fig-6 Possible revised safety criterion

Notwithstanding the inappropriateness of suggesting possible numerical vales for use in a revised criterion, it is useful to demonstrate that the suggested way forward is likely to be feasible. Consider a high design speed of, say, 400 km/h and a large gradient of, say, 2%. The values would imply a rate of change of static pressure of approximately 0.025 kPa/s, which is similar to routine conditions in passenger aircraft ascent and descent. If such a limiting rate were adopted for pressure changes in excess of 10 kPa, it would come into effect only for time intervals exceeding 400 s. Thus it would have no impact whatsoever on journeys through short tunnels. In aviation, this rate of change is regarded as acceptable for pressure changes as large as 20 kPa, whereas, for railways, such large overall changes are not currently foreseen. This method of relaxing the safety criterion would probably allow sufficiently for a large majority of people with partially-blocked Eustachian tubes. However, it would increase risk for people with totally blocked tubes so supplementary measures would also be needed to ensure that such persons receive appropriate advice before deciding to travel on a route involving potential for large overall pressure changes.

6.3 Alternative revised safety criterion

The possible revised criterion considered above has the benefit of being capable of direct assessment in relation to medical evidence. An alternative modification that is known to have been discussed retains the simple form of the existing safety criterion, but stipulates that all static pressure changes may be disregarded when it is applied. The claimed justification for this exclusion is that rates of change of the background static pressure are necessarily small (as illustrated in the preceding Section) and so their consequences can become significant only at relatively large times. Nevertheless, it does not seem reasonable to allow unspecified increases in pressure changes without specific guidance from medical specialists.

Another possible revision would be to retain the existing criterion, but to allow the possibility of violations with sufficiently low statistical probability and low consequence. Such considerations might be considered acceptable by safety specialists familiar with widespread needs for criteria based on achieving risk levels that are "*as low as reasonably practicable*".

A somewhat different approach would be to seek to reduce the probability of at-risk passengers undertaking journeys by rail without the benefit of prior medical guidance. It seems likely that this probability could be reduced to very small levels if appropriate advice were provided (to the medical profession as well as to passengers) by railways operating trains through tunnels that would violate the existing criterion because of large elevation change. Similar actions might also mitigate potential risks arising from other causes of violation – e.g. sudden loss of sealing – but this is a very different problem. First, it is potentially relevant to a large number of tunnels and second, it could cause very rapid rates of change of pressure whereas the elevation effect causes only very slow rates of change.

7 CONCLUSIONS

Attention has been drawn to some implications of the UIC health and safety criterion used by railways in the design and operation of travel through tunnels. It has been shown that adherence to the criterion is beginning to have a stronger influence on design than hitherto. Furthermore, the issues that arise can have major cost implications. The overall deductions from the paper can be summarised as follows.

1. Although the safety criterion can impact the design of any tunnel, it imposes especially strong constraints on high-speed railways in regions where large differences of elevation are required along tunnels.

2. In such tunnels, designs that easily satisfy comfort criteria – especially for sealed trains – may be deemed unacceptable because they would violate the safety criterion.

3. In some cases where a violation would occur, it is possible to identify design changes that would avoid the violation, but would do so in a manner that seems unlikely to offer any advantage for passengers. This has the potential to create a dilemma for railway designers and operators.

4. It is sometimes possible to identify alternative tunnel configurations that cause almost identical pressure histories and yet one configuration satisfies the criterion whereas another violates it. This casts doubt on the universality of effectiveness of the criterion.

5. The design inconsistencies implied by cases such as these arise primarily in long tunnels with large differences of elevation. It is possible that relatively little attention was paid to such cases when the safety criterion was originally developed. If so, there would be merit in a formal review of the criterion.

6. Possible revisions for the criterion might include:

- allow increased pressure changes provided that these do not violate prescribed limiting rates of change of pressure;
- disregard elevation changes when assessing compliance with the criterion;
- allow increased pressure changes provided that, statistically, they are sufficiently rare.

7. Any review of the criterion should include adequate professional guidance from suitably qualified medical specialists with appropriate experience.

8. A comprehensive review of the criterion would consider issues such as the probability of sudden loss of train sealing as well as issues such as large elevation change. However, a clear distinction should be maintained between effects that are possible in short time periods and those that are possible only in long periods.

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APPENDIX CASE STUDY: PAJARES TUNNEL

The generic issues raised in the body of the paper can be illustrated by reference to a particular example, namely a proposed tunnel at Pajares in northern Spain. It is envisaged that the tunnel will be almost 25 km long, that its cross-sectional area will be slightly greater than 50 m^2 and that there will be an elevation difference of about 420 m between the portals. Table 3 shows predicted fluctuations in this tunnel for a 400 m, 12 m^2 train travelling at 300 km/h. The predicted pressure changes shown in intervals of 1, 4 & 10 secs are inside the sealed train and the overall pressure change is shown for a train which is effectively unsealed.

The "sealed" pressures are based on a dynamic leakage time constant of 10 s. Smaller values will apply if, as expected, the sealing is tighter than this. Nevertheless, even with this degree of sealing, the changes in intervals of 1 s and 4 s are much smaller than those in the UIC guidelines and the maximum change in 10 s exceeds the guideline value (2.0 kPa) only at the rear of the train.

The predicted maximum overall change throughout the journey based on an assumed loss of sealing is just equal to the UIC limit and so, allowing for uncertainties, it cannot be asserted reliably that the limit would not be exceeded in a real journey. However, this conclusion is valid only for trains travelling uphill. The predicted maximum overall change for downhill travel is much smaller and, of special relevance to the present paper, the predicted maximum *excluding* the background change in static pressure is smaller still.

No attempt is made herein to suggest how the designers of this tunnel should respond to this issue. That is a matter for the design team and the railway operator. However, the tunnel provides a useful illustration of the influence of the current safety criterion. The criterion is a limiting factor at 300 km/h and it would exclude any realistic possibility of travel at the greater design speeds than are becoming common in tunnel design – especially for future-proofing of the design, but also for immediate use.

Table-3 Predicted pressure changes in Pajares Tunnel [kPa]

Gradient	**COMFORT CRITERIA**						**SAFETY CRITERION**	
	Δp in 1s		***Δp in 4s***		***Δp in 10s***		***Max overall Δp***	
	Nose	*Tail*	*Nose*	*Tail*	*Nose*	*Tail*	*Nose*	*Tail*
Downhill	0.40	0.34	0.85	1.18	1.59	2.55	4.86	7.24
Horizontal	0.33	0.33	0.83	1.15	1.55	2.49	6.21	5.43
Uphill	0.31	0.31	0.76	1.07	1.42	2.30	9.89	10.00